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Towards Reducing Electronic Waste in a Sustainable Closed-Loop Supply Chain

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Abstract

The increasing use of electronic goods worldwide has led to a significant increase in the amount of waste generated from their consumption, resulting in a primary environmental concern. This study aims to provide a systemic framework for reducing electronic waste by considering the benefits of a closed-loop sustainable supply chain. To achieve this goal, a systematic literature review was conducted to identify influential factors related to the green supply chain. Based on the identified factors in this section regarding electronic waste, a systematic framework was devised for the technology park companies' chain in Yazd. Accordingly, a systemic structure was formed utilizing a fuzzy cognitive mapping technique based on the current state. The statistical population of this study consisted of industry experts in e-waste in Iran. The initial criterion for identifying these individuals was having at least one international research publication or a minimum of 10 years of work experience in this field. These individuals were selected using the snowball sampling method. After completing the snowball sampling process, 72 experts were selected. Based on this framework, forward and backward scenarios were created to offer practical solutions for addressing the problem of electronic waste in Iran. The results of this study suggest that instead of discarding a significant portion of electronic waste, efforts should be focused on cost reduction through better recycling processes. By implementing a closed-loop sustainable supply chain, businesses can recover valuable resources from electronic waste, reduce their carbon footprint, and ultimately contribute to creating a more sustainable future.

Keywords: Sustainable supply chain, Closed-loop supply chain, Electronic waste.

1 | Introduction

The due to the increasing production of waste worldwide [1], protecting human civilization from the harmful effects of human-generated waste has become a noteworthy concern among researchers [2]. Waste is any solid, liquid, or gaseous material discarded or left over from using raw materials on land or in the atmosphere

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[3], [4]. One solid waste category is electronic waste, which has garnered considerable attention in recent years due to advancements in information technology, electronics, and the electrical industries [5], [6]. Global electronic waste production is nearly 40 million tons annually, constituting approximately 5% of the total worldwide solid waste generated [7]. This growing volume of electronic waste production has become an environmental issue and a challenge [8]. Electronic waste is the waste generated from electronic and electrical equipment, parts, and items that are discarded parts and items. Electronic waste is generated by all components and items of electronic and electrical equipment components, components items, and items that are discarded without undergoing reuse [9]. This type of waste is generated from various sources such as governments, companies, and households [10], with the highest share of electronic waste production coming from the IT and consumer electronics industries [11] due to the increasing amount of electronic waste, its disposal and recycling are of particular importance [12].

On the other hand, recycling electronic waste holds immense significance due to valuable resources such as metals, glass, plastics, etc. [13]. Proper waste management and secure electronic waste disposal have emerged as worldwide priorities to mitigate health risks to humans and environmental degradation [14]. In other words, improper recycling and disposal of electronic waste will not only harm the environment and public health [15] but also result in significant costs such as loss of valuable raw materials [16], negative public image and perception [17], customer dissatisfaction [18], [19], and more. Improper disposal and recycling of electronic waste affect the performance of various companies and organizations from three economic, environmental, and social aspects of sustainable supply chain management [20].

The work [22] demonstrated that a sustainable supply chain guarantees the sustainable performance of different companies and organizations. The sustainable supply chain is defined as a systematic integration of thinking, strategy, and action in supply chain management in three aspects: financial, environmental, and social performance [22]. Sustainable supply chain practices empower manufacturing companies and specialists to contemplate potential adverse consequences of supply chain activities on the environment, society, and economy and endeavor to mitigate their detrimental impacts [23]. Despite the substantial potential of a sustainable supply chain to diminish the amount of electronic waste, the recycling process within such a framework would be enhanced by emphasizing the closed-loop approach within this supply chain [24].

The closed-loop supply chain is characterized as a system encompassing design, operation, and control to reinstate value to a product throughout its lifecycle via pre-planned recycling mechanisms [25]. Collecting and re-manufacturing used items directly within the closed-loop supply chain mitigates electronic waste pollution and carries numerous economic advantages [26]. For example, according to Apple's 2017 report, the company recycled approximately 1,900 kilograms of aluminum, 800 kilograms of copper, 550 kilograms of cobalt, 7 kilograms of silver, and 0.3 kilograms of gold. This recycling effort generated $100 billion from these reclaimed metals originating from electronic waste while also contributing to reducing environmental harm [27]. This indicates that dealing with electronic waste recycling in the form of a sustainable closed-loop supply chain can bring economic, environmental, and social benefits, including increased income [28], reduction in the use of natural resources [29], improved productivity [30], reduction in pollution caused by waste disposal [31], positive social reputation among customers [32], and more for various organizations.

Consequently, employing a sustainable closed-loop supply chain approach in electronic waste management can yield numerous benefits across the entire supply chain. As a result, implementing a sustainable closed-loop supply chain in electronic waste management can provide numerous benefits throughout the supply chain. On the other hand, nowadays, with the development and advancement of information and communication technology, as well as the internet, electronic waste is increasing in various countries, especially in Iran, which has become one of the major concerns and worries of officials, managers, and researchers. Based on various reports in this field, over 4,000 tons of electronic waste are produced annually in Iran, managed through basic methods such as destruction, burial, and sale to other countries.

Such electronic waste management can impose irreparable damages to the environment and economy of the country. On the other hand, reviewing studies conducted in the field of electronic waste in recent years, most

of the studies have focused on the disposal, recycling, and management of electronic waste [32–34], the consequences and effects of electronic waste [35], [36], challenges and obstacles to proper management of electronic waste in sustainable development [36–38], and more. Fewer studies have delved into the factors that wield influence and offered appropriate remedies for mitigating electronic waste. Additionally, the suggested solutions presented in this section must transcend vagueness and be assessed as a tailored roadmap for the present circumstances in Iran. This study accentuates the significance of a sustainable closed-loop supply chain in diminishing electronic waste within Iran, considering the existing state of infrastructure and the factors that influence the closed-loop supply chain. This research aims to propose a systemic framework for the appropriate implementation of a closed-loop supply chain using its advantages to reduce electronic waste in Iran. Accordingly, the main objective of the current study is to identify the influential factors in a sustainable closed-loop supply chain, establish a structural system, and provide scenarios to enhance the efficiency of the closed-loop supply chain in electronic waste management in Iran.

Continuing with the article, Section 2 delves into the literature review of the research topic. Section 3 discusses the research methodology, including the research process, data acquisition methods, and data analysis techniques. Section 4 elaborates on both quantitative and qualitative research findings. Sections 5 and 6 further discuss the outcomes obtained from Section 4, encompassing managerial and research recommendations, as well as addressing the research limitations and conducting an in-depth analysis and examination.

2 | Literature Review

2.1 | Electronic Waste

The exponential proliferation of e-waste finds its roots in its intricate constitution [39]. Electronic devices comprise a conglomerate of materials, encompassing precious metals like gold, silver, copper, and rare earth elements, alongside an array of plastics, glass, and potentially perilous substances such as lead, mercury, and flame-retardant compounds [40]. This intricate amalgamation endows e-waste management with distinctive hurdles, necessitating judicious sorting, recycling methodologies, and disposal practices that temper environmental ramifications and harness resource reclamation. Central to the e-waste problem is the predicament of inadequate disposal. Without responsible stewardship, e-waste can usher in dire ramifications for both human well-being and the ecological equilibrium [41]. The toxic constituents within electronic devices can infiltrate soil and water sources, culminating in contamination and detrimental health repercussions [8]. Unregulated recycling procedures, prevalent in certain regions, often encompass hazardous techniques like open incineration or chemical baths, resulting in the emission of toxic fumes and pollutants into the atmosphere, thus amplifying the environmental toll exacted by e-waste.

Nonetheless, the e-waste quandary concurrently unfurls vistas for sustainable resource management and initiatives rooted in the circular economy [42]. Extracting valuable metals from e-waste through meticulous recycling processes conserves scarce natural resources and curtails the necessity for ecologically destructive mining undertakings. Furthermore, embracing the tenets of the circular economy, wherein products are designed with durability and recyclability at their core, can prolong the lifespan of electronic devices and inculcate conscientious consumption patterns [43].

2.2 | Sustainable Supply Chain

A sustainable supply chain, often green or eco-friendly, has emerged as a fundamental approach in contemporary business practices [44]. It embodies a holistic strategy that integrates environmental, social, and economic considerations into every facet of the supply chain [45]. The core tenet of a sustainable supply chain is to minimize negative impacts on the environment while simultaneously maximizing value creation for all stakeholders involved [46]. In a rapidly evolving world marked by increasing awareness of environmental and social issues, the concept of a sustainable supply chain has gained prominence [47]. Traditional supply chains have historically focused on cost efficiency and operational effectiveness, often disregarding the broader

environmental and societal implications [48]. However, as the adverse effects of climate change, resource depletion, and social inequality become more apparent, businesses recognize the need to transition to a more sustainable paradigm [49].

The pillars of a sustainable supply chain revolve around three main dimensions: environmental, social, and economic [50]. In the environmental sphere, the focus is on reducing carbon emissions, conserving energy and water, minimizing waste generation, and promoting responsible sourcing of raw materials [51]. This involves optimizing transportation routes, adopting clean energy solutions, and implementing recycling and circular economy practices [52]. The social dimension of a sustainable supply chain emphasizes ethical labor practices, human rights, and fair working conditions. Suppliers are expected to adhere to international labor standards, prohibit child and forced labor, and provide safe and healthy working environments [53]. Collaboration with suppliers to ensure decent wages, gender equality, diversity, and inclusion is pivotal in creating a socially responsible supply chain [22].

Economic sustainability within the supply chain hinges on creating long-term value for all stakeholders [46]. While immediate cost reductions are a goal, a sustainable supply chain recognizes that short-term savings should not come at the expense of long-term stability [54]. Resilience to disruptions, fostering innovation, and building lasting relationships with suppliers contribute to the economic vitality of a sustainable supply chain [55]. The benefits of a sustainable supply chain are multifold. Organizations that adopt such practices can mitigate operational risks, enhance brand reputation, and meet the growing demand from consumers for eco-friendly products. Regulatory compliance becomes streamlined as businesses align their operations with evolving environmental regulations [56]. Additionally, a sustainable supply chain can yield cost savings over the long term by optimizing resource usage and reducing waste [57].

2.3 | Closed-Loop Supply Chain

The closed-loop supply chain has become a paradigm shift in modern management [58]. Rooted in sustainability and environmental stewardship, this approach challenges traditional linear supply chains by advocating for the integration of reverse logistics, recycling, and resource recovery into every product lifecycle stage [25]. The primary objective of a closed-loop supply chain is to minimize waste generation, promote resource efficiency, and create a regenerative system that reduces the strain on natural resources and mitigates environmental impacts [59].

The traditional linear supply chain model, characterized by a linear progression from raw material extraction to production, consumption, and eventual disposal, has long been associated with resource depletion, environmental degradation, and the generation of vast amounts of waste. In contrast, the closed-loop supply chain operates on the premise of a continuous cycle where products, components, and materials are reintegrated into the production process, extending their useful life and minimizing the need for new resources [60].

At the core of the closed-loop supply chain lies the concept of reverse logistics, which entails the collection, refurbishment, remanufacturing, and recycling of used products and materials [30]. This approach transforms discarded products into valuable resources, reducing the strain on natural ecosystems and curbing the environmental burdens associated with raw material extraction and waste disposal [61]. One of the significant drivers behind the adoption of closed-loop supply chains is the escalating concern for environmental sustainability [62]. The alarming rates of resource depletion, climate change, and pollution have spurred consumers and businesses to demand more responsible production and consumption practices [63]. The closed-loop model offers a compelling solution by conserving raw materials, curbing energy consumption, and mitigating the carbon footprint associated with production [64].

Moreover, a closed-loop supply chain has distinct economic advantages. By recovering and reusing materials, businesses can reduce production costs and the dependency on fluctuating raw material prices. Remanufacturing and refurbishing used products often save costs while providing consumers with more

affordable alternatives [65]. This can enhance customer satisfaction and brand loyalty and even open new markets for products with reduced environmental impact [66].

3 | Literature Review

In terms of its purpose, this study falls under the classification of developmental applied research. The data collection approach aligns with survey descriptive research. In this research, it is about the implementation of a sustainable closed-loop supply chain in electronic waste. The growth of electronic waste production has caused countries to try to compensate for various environmental damages and create suitable income by recovering and reusing electronic waste. For this purpose, a system framework has been designed using experts in Iran. The primary aim of this thesis was to identify the factors that influence the implementation of a sustainable closed-loop supply chain through a systematic review. The systematic review method was first introduced by [67]. Subsequently, a comprehensive framework for managing electronic waste in Iran was devised employing the context of electronic waste management. *Fig. 1* illustrates the research process stages.

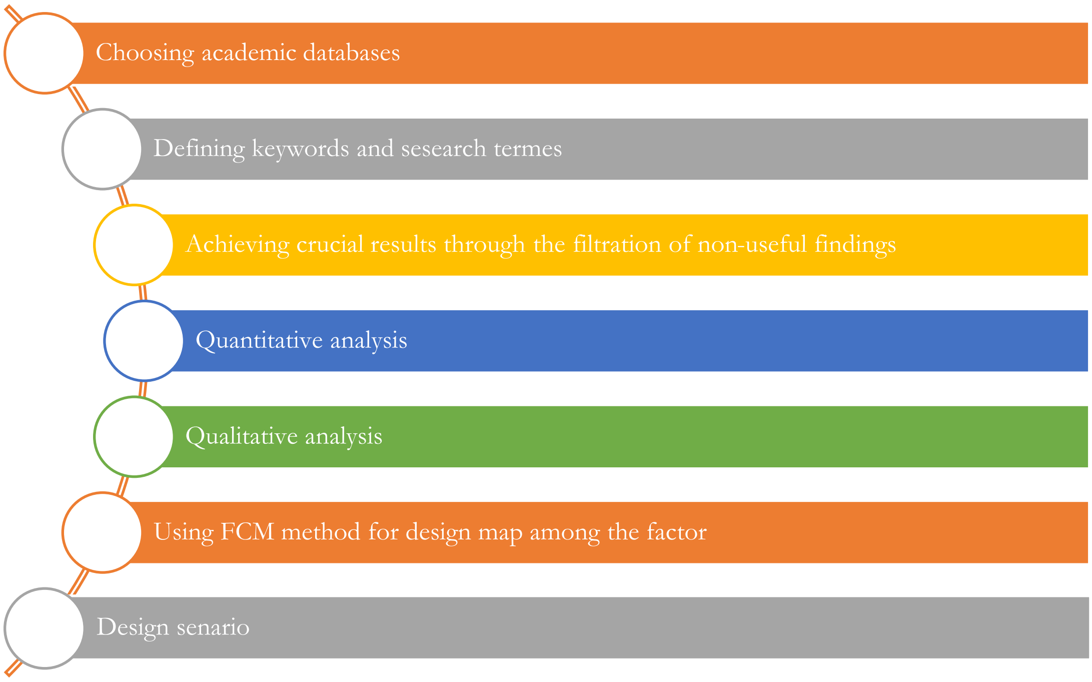

Fig. 1. Research process stages.

Based on *Fig. 1*, the databases with the highest number of articles indexed in this field were initially examined. Expert opinions from academia were utilized to identify these databases. For this purpose, the Scopus and Web of Science databases were selected. In the next stage, relevant keywords were employed within these databases to search for articles in this field. The chosen keywords were based on prior research in the domains of sustainable supply chain and closed-loop supply chain. The keywords used for the database searches are outlined in *Table 1*.

Table 1. Keywords used in the study.

Closed Loop	Sustainable	Supply Chain
Closed loop	Sustainability	Supply chain
Closed-loop	Sustainable	SC
Reverse	Green	
Remanufacturing		
Reuse		

The search domain was confined to the articles' titles, abstracts, and keywords. Following data collection from various databases, the third phase involved eliminating articles with low-value content within this field. Initially, language filters were employed on these databases utilizing the English language criterion. Subsequently, among the gathered texts, only articles were subjected to scrutiny. Based on the selected articles,

subsequent filtering mechanisms were deployed after applying the initial two filters. These processes are illustrated in *Fig. 2*.

Based on *Fig. 2*, selecting articles from two databases began by initially eliminating articles with similar titles in the two databases. Subsequently, through an analysis of the article titles, the quantity of articles was further reduced. Among the articles displaying pertinent titles with respect to the research literature, a detailed examination of the abstract texts was conducted. By excluding articles that lacked alignment with the overall research content based on their abstracts, a subset of articles remained, demonstrating relevance to the present research in terms of both title and abstract. Continuing the systematic review procedure, superfluous articles were excluded following a thorough assessment of the complete texts. This meticulous process led to the identification of 46 article titles that are pertinent to the research, as guided by the systematic review conducted in this section.

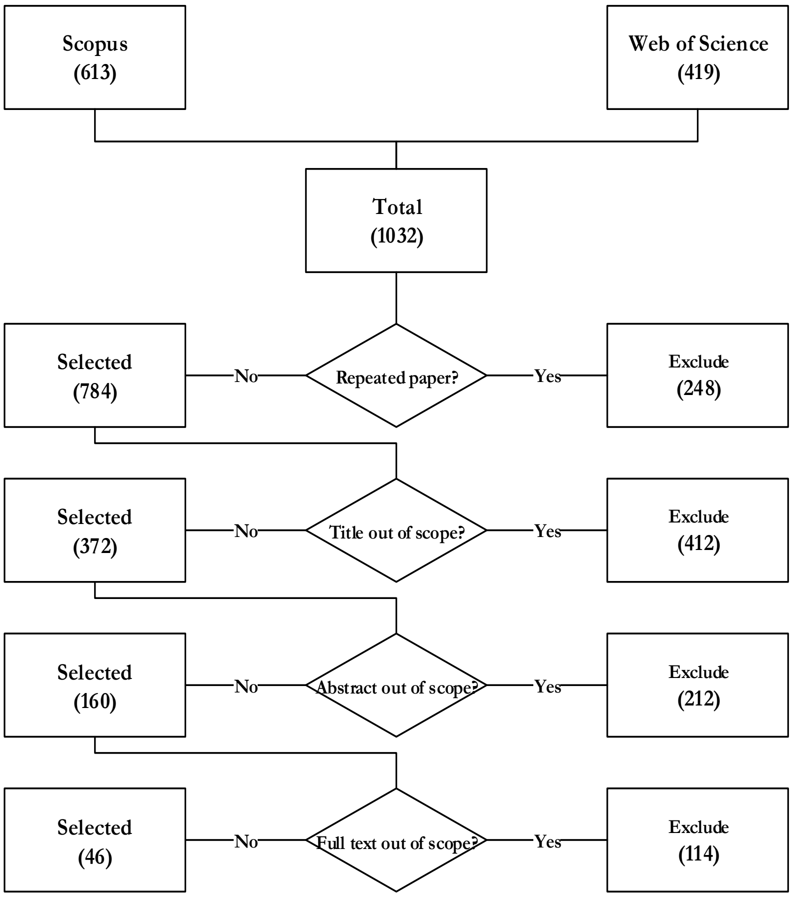

Fig. 2. Steps of systematic review.

Referring to *Fig. 1*, the fourth phase of this study involved conducting a quantitative analysis of the outcomes derived from the systematic review conducted within the sustainable closed-loop supply chain sphere. This analysis encompassed scrutinizing and evaluating trends in article numbers across recent years and exploring the interplay of keywords prevalent within the research field.

Proceeding to the fifth stage, the research delved into a qualitative analysis of the remaining 46 articles. The factors influencing the sustainable closed-loop supply chain were probed and dissected through a comprehensive review of these articles.

Moving on to the sixth step, a fuzzy cognitive map was meticulously crafted among the identified factors. This map served as a means to assess and dissect the intricate relationships between the factors, presenting them within a systemic framework. The procedure for constructing a fuzzy cognitive map in this study was grounded in the work conducted by [68]. This study's statistical population comprises experts in Iran's e-waste industry. In this context, the term "experts" refers to individuals in Iran who possess scientific or professional

expertise across diverse research domains concerning e-waste. The initial criterion for identifying these individuals was possessing at least one international research publication or a minimum of 10 years of practical experience in this field. The selection of these individuals was executed through the snowball sampling method. Following the completion of the snowball sampling process, a total of 72 experts were ultimately chosen. A systematic approach was taken to gather information from these experts. Initially, utilizing Scopus, three experts who had conducted scientific research in the pertinent field and were based in Iran were identified. Subsequently, leveraging the insight of these initial experts and adhering to the snowball method, a network of additional experts across the country was established. To finalize the questionnaire content, each expert was requested to provide input. They were sent the questionnaire via email and were guided through the process via telephone to ensure clarity and accuracy in their responses.

Using the questionnaire, an exploration was conducted into the present status of each stakeholder within the electronic waste sector in Iran. A comprehensive representation of the current landscape was visualized based on the collected data. In the final stage of the study, backward and forward scenarios were devised using the acquired fuzzy cognitive map. FCMAPPER software was employed to craft these scenarios. Three agents with notably high indegree levels were selected for the backward scenarios, while three agents displaying substantial outdegree levels were chosen for the forward scenarios. The objective of the backward scenarios was to unearth the underlying causes of variations within a specific agent. A series of steps was outlined to guide researchers in enhancing a particular agent's performance. Conversely, forward scenarios illustrated the sequence of agents within the system that could benefit from improving a particular agent's performance [69].

4 | Biometric Analysis and Result

This section presents a quantitative analysis of the data obtained from the study. The figure below illustrates the number of published articles in this field each year up to the end of February 2023.

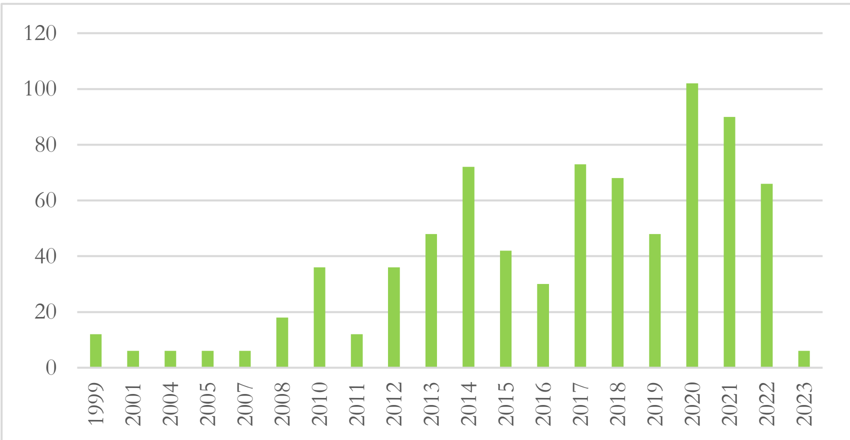

Fig. 3. Published articles each year until the end of February 2023.

Based on the obtained output, the VOSviewer software was used to create a relationship map among the most important keywords. Given this section's extensive network of connections, keywords that appeared more than 30 times were considered. As a result, 28 relevant and frequently occurring keywords were extracted. *Fig. 4* visualizes this process.

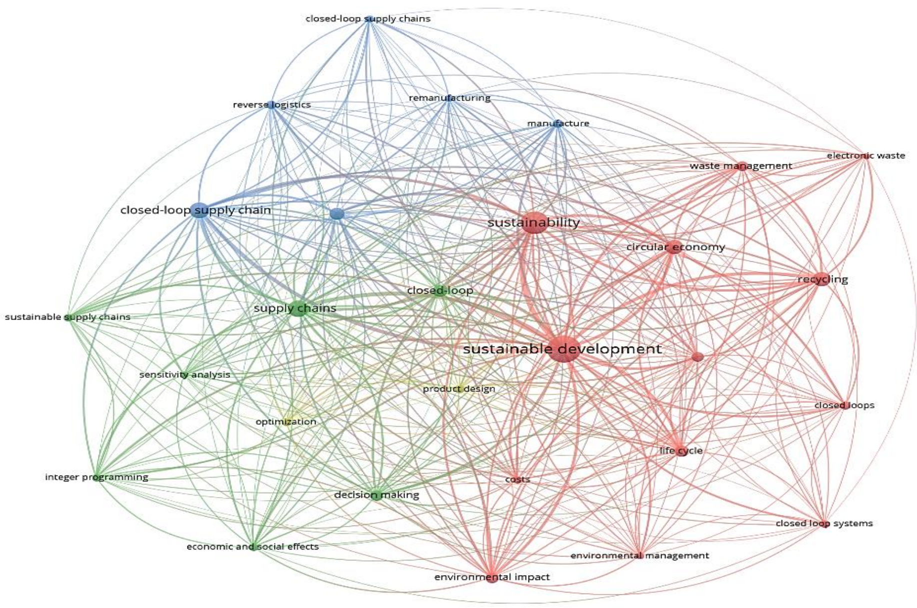

Fig. 4. The relationship map between keywords.

After conducting a qualitative analysis in this study, the influential factors on the sustainable closed-loop supply chain are identified and presented in *Table 2*.

Table 2. Effective factors on the establishment of a sustainable closed-loop supply chain.

Factor	References
1- Improved customer service and satisfaction	[70], [71]
2- Less waste and extract value added from it	[71–74]
3- Tangible cost saving	[71], [73], [75–78]
4- Improved Inventory tracking	[71],[77], [79], [80–82]
5- Improved product quality and design	[71], [83–86]
6- Improved transportation	[70], [74], [77], [80], [87–89]
7- Selection of quality suppliers	[72], [76], [88], [90–92]
8- Improve flexibility in manufacturing	[74], [75], [88], [93–96]
9- Reduce administrative bureaucracy	[72], [86], [90], [97], [98]
10- Proper training of employees	[80], [87], [97], [99], [100]
11- Use of appropriate equipment	[73], [74], [80], [81], [92], [99], [100]
12- Promotion of information sharing	[73], [80], [88], [95], [99], [101]
13- Promotion of system security	[73], [80], [94], [99], [101], [102]
14- Promotion of maintenance	[79], [80], [88], [91], [103]
15- Use of opening manufacturing	[77], [94], [96], [104]
16- Reduce of pollutants	[70], [80], [82], [83], [85], [90], [98], [105]
17- Optimism in product distribution	[77], [82], [83], [96], [100], [103], [104], [106], [107]
18- Creating equal employment opportunities	[73], [75], [86], [98], [101], [108], [105]
19- Optimizing the total cost of facilities with certain environmental levels and capacity levels	[77], [96], [98], [104], [109], [110]
20- Disassemble parts of recycled products from the source	[73], [79], [83], [97], [98], [104], [107], [109]
21- Facilitate product return processes	[73], [77], [78], [103], [109], [111]
22- Promotion of price competition among retailers	[76], [81], [84], [92], [97], [108–110]
23- Reducing energy consumption in the manufacturing sector	[70], [77], [79], [83], [85], [103], [105], [109], [111]
24- Improved material recovery	[72], [77], [92], [93], [97], [108], [107], [111], [112]

Using the questionnaire and *Table 2* as a reference, experts evaluated the current status of these factors in Iran. Subsequently, employing the stages of the fuzzy cognitive map technique, a system was designed to illustrate the multidimensional relationships between the factors and their respective intensities. This systemic structure is depicted in *Fig. 5*, created using the Pajek software.

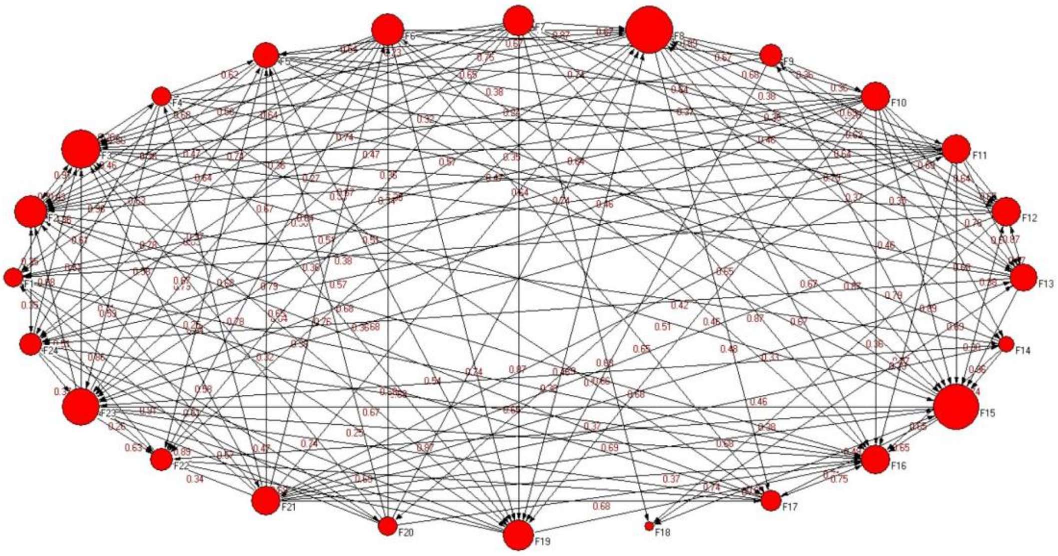

Fig. 5. Fuzzy cognitive map of establishing a sustainable closed-loop supply chain in electronic waste.

The fuzzy cognitive map presented in this section was analyzed using Fcmapper software. *Table 3* offers general information about the map.

Table 3. General information about the map.

Density	Hierarchy Index	Total Nr. Factors	Total Nr. Connections	Nr. NoConnection	Nr. SelfLoops	Nr. Regular Connections
0.300347	deactivated by author	24	173	0	0	173

Fig. 6 displays the outdegree values for each factor. Outdegree represents the degree of influence a factor exerts on other influential factors in this section.

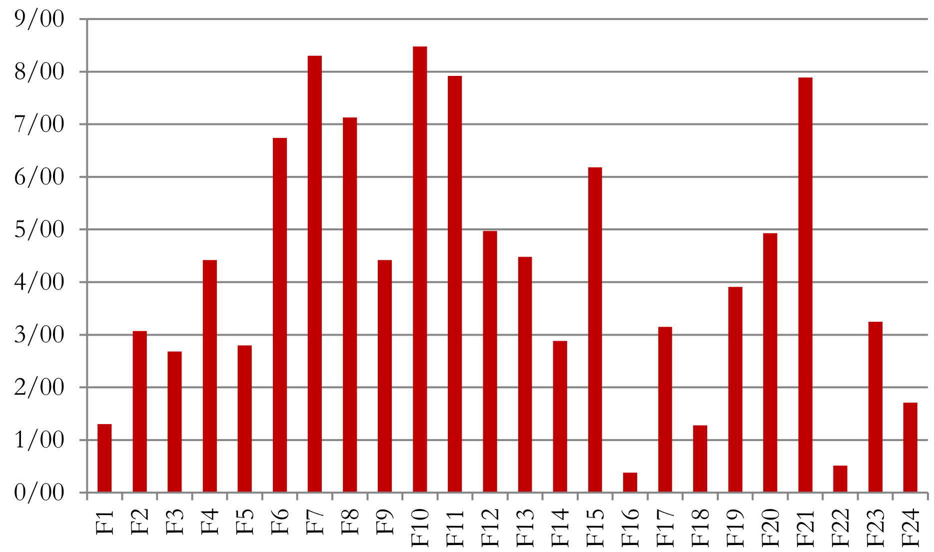

Fig. 6. Outdegree values for each factor.

Fig. 7 displays the Indegree values for each factor. Indegree represents the degree to which other influential factors influence a factor in this study.

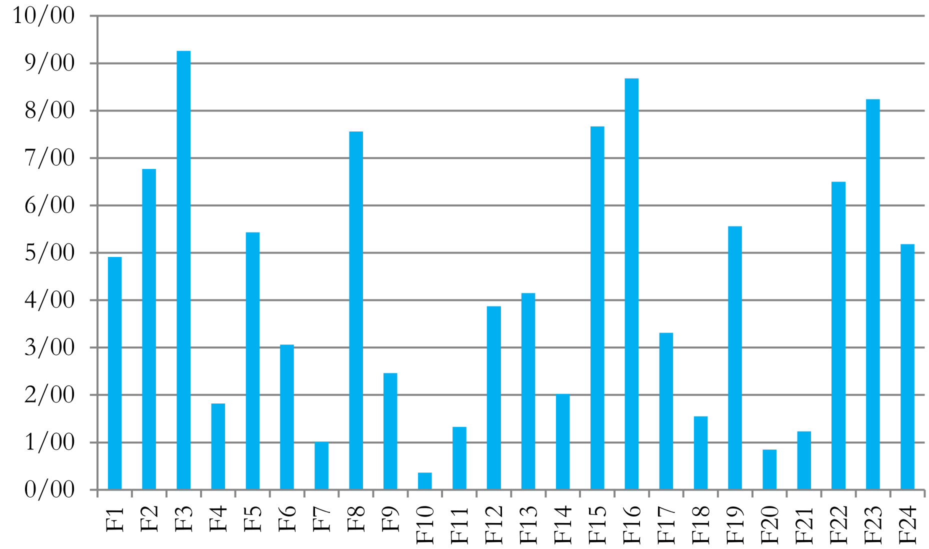

Fig. 7. Indegree values for each factor.

Fig. 8 illustrates the centrality values for each factor. These centrality values for each factor are calculated as the sum of their indegree and outdegree values.

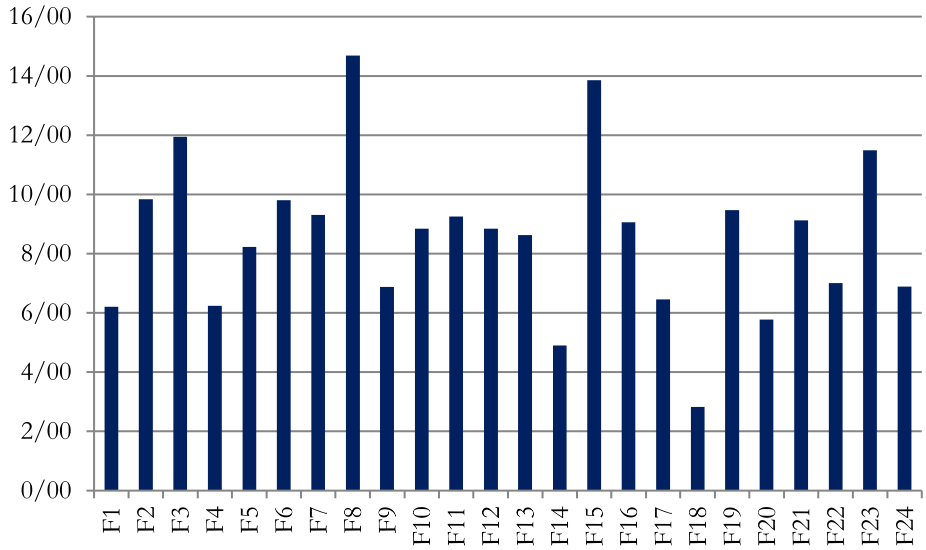

Fig. 8. Centrality values for each factor.

In this section, scenarios have been developed to enhance the systemic structure created in this study and reduce electronic waste in Iran. For backward scenarios, we focused on three factors with high in-degree values, and for forward scenarios, three factors with the highest outdegree values were considered. Scenario paths were designed using the Fcmapper software.

The study investigated the system's learning function from the environment, employing the sigmoid function to stabilize the system with the fewest iterations. The first backward scenario was designed for the 'tangible cost-saving' factor. In this scenario, influential factors on this factor were initially held constant in the system, and their impact on the 'tangible cost-saving' factor was examined. Results from the software analysis showed that the 'less waste and extract value added from it' factor had the greatest influence on the 'tangible cost-saving' factor.

To further understand the 'less waste and extract value added from it' factor's dynamics, its influential factors were separately analyzed to identify the one with the most significant impact on this factor. This analysis revealed that the 'tangible cost-saving' factor had the greatest influence on the 'less waste and extract value added from it' factor. Since this factor was already included in the backward scenario cycle, the backward

scenario path in this section was concluded. *Fig. 9* illustrates the backward scenario path for the 'tangible cost-saving' factor.

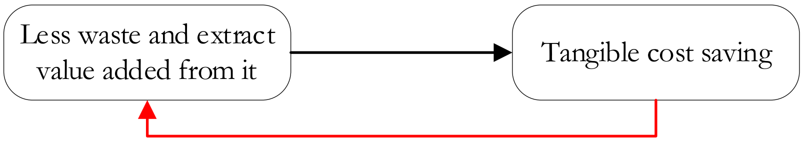

Fig. 9. The backward scenario path for the tangible cost saving factor.

As previously described, two backward scenario paths have been developed for the 'reduce of pollutants' and 'reducing energy consumption in the manufacturing sector' factors. *Figs. 10* and *11* depict these backward scenario paths.

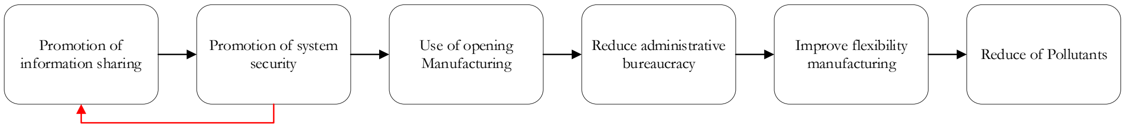

Fig. 10. The backward scenario path for the reduction of pollutants factor.

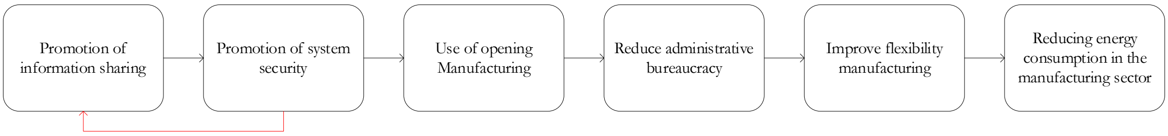

Fig. 11. The backward scenario path for reducing energy consumption in the manufacturing sector factor.

This study developed three forward scenarios for the factors with the highest outdegree values. One of these forward scenarios focused on the 'proper training of employees' factor, and a scenario path was created for it. Using the Fcmapper software, we first fixed the 'proper training of employees' factor and examined its effects on related variables.

Within this analysis, the 'promotion of maintenance' factor was identified as having the greatest influence stemming from the 'proper training of employees' factor. Subsequently, the forward scenario path for the 'promotion of maintenance' factor was established, and its impact on the relevant factors was explored. Further investigation revealed that the 'improved product quality and design' factor significantly influenced the 'promotion of maintenance' factor's scenario. We then fixed the 'improved product quality and design' factor to study its effects on other related factors.

Within this analysis, the 'improved product quality and design' factor was found to have the greatest influence on the 'improved customer services and satisfaction' factor. We continued the forward scenario path by fixing the 'improved customer services and satisfaction' factor and investigating its impact on associated factors. In this examination, the 'disassemble of parts of recycled products from the source' factor emerged as having the most substantial influence stemming from the 'improved customer services and satisfaction' factor. Continuing with this fixed factor, we identified the influence values of the factors on the affected variables. This analysis identified the 'improved transportation' factor as having the most significant influence from the 'disassemble of parts of recycled products from the source' factor. We then focused on the 'improved transportation' factor to study its effects on other influenced factors. Here, the 'optimism in product distribution' factor was found to have the greatest influence on the 'improved transportation' factor's scenario. Continuing with the 'optimism in product distribution' factor, we explored its effects on the affected factors. Finally, the 'Improved customer services and satisfaction' factor was identified as having the most substantial influence stemming from the 'optimism in product distribution' factor. Since this factor already existed in the scenario loop, the scenario path concluded. *Fig. 12* illustrates the forward scenario path for the 'proper training of employees' factor.

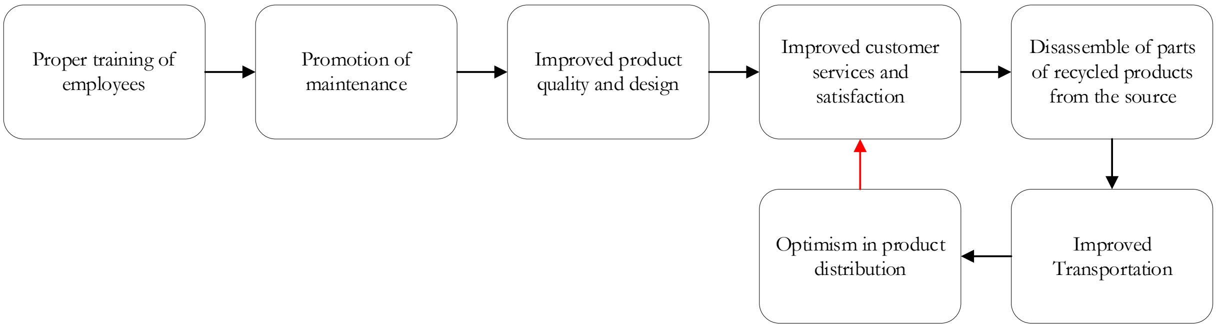

Fig. 12. The forward scenario path for the Proper training of employees factor.

Following the steps described for the forward scenario path in this study, two forward scenario paths were developed for the 'selection of quality suppliers' and 'facilitate product return processes' factors, as previously detailed. *Figs. 13* and *14* illustrate these forward scenario paths.

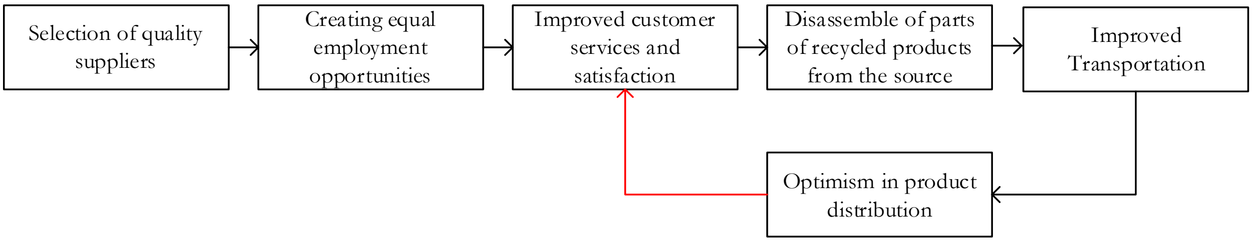

Fig. 13. The forward scenario path for selecting quality supplier's factor.

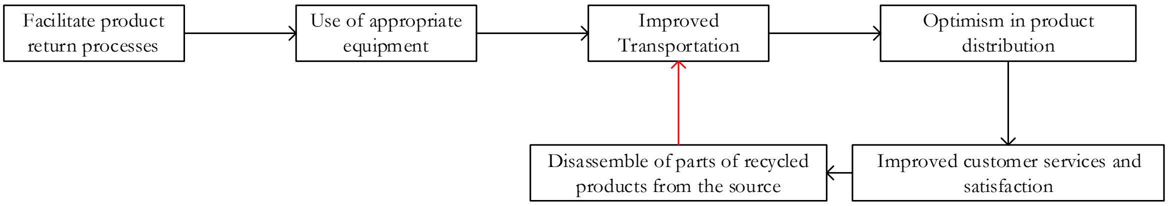

Fig. 14. The forward scenario path for the facilitated product return processes factor.

5 | Discussion and Challenges

The management of electronic waste has seen the emergence of innovative approaches, such as sustainable supply chains and closed-loop supply chains, which have proven highly effective in mitigating the adverse consequences of electronic waste. The primary aim of the sustainable supply chain is to foster collaboration among producers, suppliers, and consumers to utilize recycled materials and resources in the manufacturing and distribution of goods. This approach helps curb the import of raw materials, reduce waste generation, and ensure the sustainable use of natural resources.

Conversely, the closed-loop supply chain focuses on increasing the recycling and recovery of electronic waste. It involves processes like disassembling electronic components, recovering valuable materials, and recycling substances like plastic and glass, all aimed at minimizing the negative impact of electronic waste.

This research aimed to develop a sustainable closed-loop supply chain structure that harnesses the potential of both the sustainable supply chain and the closed-loop supply chain for more effective electronic waste management. To accomplish this, a systematic study was undertaken to identify the key factors crucial for establishing a sustainable closed-loop supply chain, eliminating redundancy in existing literature. Consequently, 24 influential factors were identified for creating a sustainable closed-loop supply chain.

Considering the substantial volume of electronic waste in Iran and the imperative of addressing its severe environmental consequences, this research sought to leverage the advantages of these supply chain models. A systemic structure was therefore devised in this research to illustrate the nature, intensity, and interconnections among these factors in their present state. Building on the systemic structure, backward and forward scenarios were designed to enhance the overall system and performance.

The findings within the developed systemic structure reveal that the density rate for this structure is approximately 0.3. This value indicates that, among all potential relationships among the factors, experts identified about 30 percent of them as significant. It's worth noting that there is no predefined threshold for the density rate in a fuzzy cognitive map [69].

One of the key findings of this research is that the factor 'improve flexibility in manufacturing' has the highest centrality rate. This suggests that this factor wields substantial influence over others within the system. Consequently, focusing on enhancing flexibility within the closed-loop supply chain of electronic waste holds the potential to reduce waste and generate positive environmental impacts. This finding aligns with prior research [113], [114].

Another critical finding from the research pertains to the 'tangible cost saving' factor. It is crucial to emphasize the 'less waste and value extraction' factor to improve this factor. This finding implies that, rather than discarding electronic waste or low-value materials, they can be repurposed to create higher-value products, resulting in cost savings. This conclusion aligns with previous research [115], [116].

In the second section of research findings, it becomes evident that enhancing the 'reduce of pollutants' factor requires a focus on the 'promotion of information sharing'. Effective information sharing can enhance the security of information maintenance systems and electronic waste resources, setting the stage for reform. Open production of electronic waste not only mitigates environmental pollution but also creates economic opportunities by reducing administrative bureaucracy. Reduced administrative bureaucracy within the closed-loop sustainable electronic waste supply chain fosters production flexibility, reducing pollution levels, including water and soil pollution, greenhouse gas emissions, and more. This aligns with other research results [117], [118].

Furthermore, the forward scenario of this research demonstrates that improving the 'proper training of employees' factor yields better results in the 'promotion of maintenance' factor. This finding is in harmony with earlier research [119], [120]. Lastly, the findings suggest that enhancing the 'promotion of maintenance' factor is a foundation for improving the 'improved product quality and design' factor.

While this article proposes practical solutions for enhancing electronic waste recycling within a sustainable closed-loop supply chain, several challenges impede its implementation. One notable challenge is the lack of awareness among members of the sustainable closed-loop supply chain regarding the benefits of these solutions. This deficiency can disrupt the entire supply chain, leading to disturbances [121], [122]. Another significant challenge pertains to the coordination among members of the sustainable closed-loop supply chain. This challenge can manifest in various ways, including the absence of synchronized efforts by all members to establish a sustainable closed-loop supply chain and a lack of clarity regarding the roles and responsibilities of each member within the supply chain, among others.

Furthermore, non-compliance with government regulations and standards, along with varying levels of recognition and analysis among members of the sustainable closed-loop supply chain, hinders the adequate performance of the system. This issue has been recognized as one of the most critical challenges in achieving consensus [123].

6 | Conclusion

In today's world, electronic devices are pervasive in every aspect of life, leading to a substantial increase in the production waste generated by these products. A closed-loop supply chain tailored to electronic waste management can effectively handle this surge in waste volume and offer various advantages to organizations.

This research was undertaken to craft a systematic framework for the sustainable utilization of electronic waste within a closed-loop supply chain structure. The research findings revealed that among the 24 factors identified through a systematic review, the 'improve flexibility in manufacturing' factor emerged as the most central factor within the system. Three backward and forward scenarios were proposed to enhance the established systemic structure.

The outcomes of this study offer valuable research avenues for fellow researchers interested in this domain. Notably, within the backward scenario section, the 'less waste and value extraction' and 'promotion of information sharing' factors were identified as the catalysts for initiating change in the systemic structure. Researchers keen on this subject can explore methods to enhance these factors and develop practical strategies for their effective utilization. It is also advisable for future researchers to leverage the systemic structure developed in this study and introduce a temporal dimension when examining and analyzing changes in these factors over time. This longitudinal approach can provide deeper insights into the dynamics of electronic waste management. Furthermore, considering the challenges unveiled in this study, governments must bolster their role as policymakers in this domain through further research and practical policy implementation.

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